

Probing the cosmic acceleration history and the properties of dark energy from the ESSENCE supernova data with a model independent method

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Abstract

With a model independent method the expansion history $H(z)$, the deceleration parameter $q(z)$ of the universe and the equation of state $w(z)$ for the dark energy are reconstructed directly from the 192 SNe Ia data points, which contain the new ESSENCE SNe Ia data and the high redshift SNe Ia data. We find that the evolving properties of $q(z)$ and $w(z)$ reconstructed from the 192 SNe Ia data seem to be weaker than that obtained from the Gold set, but stronger than that from the SNLS set. With a combination of the 192 SNe Ia and BAO data, a tight constraint on Ω_{m0} is obtained. At the 1σ confidence level $\Omega_{m0} = 0.278^{+0.024}_{-0.023}$, which is highly consistent with that from the Gold+BAO and SNLS+BAO.

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I. INTRODUCTION

In order to explain the present cosmic accelerating expansion discovered firstly from the Type Ia Supernovae (Sne Ia) [1, 2, 3, 4, 5, 6], dark energy (see [7, 8, 9, 10] for recent reviews) is usually assumed to exist in the universe. Dark energy is an exotic energy component with negative pressure, and presumably began to dominate the evolution of the universe only recently. Although it has been studied for nearly one decade, its nature is still puzzling.

In general there are two kinds of methods to reconstruct the properties of dark energy from the observation data directly. One is to assume an arbitrary parametrization for the equation of state of dark energy, $w(z)$, the potential of dark energy, $V(z)$, the Hubble parameter, $H(z)$, or the luminosity distance $d_L(z)$ with some arbitrary constants. By determining these constants from the observational data, we can obtain the evolving properties of dark energy. Different ways of parametrization have been discussed in Refs. [11, 12, 13]. The other is the no-parametric method, which usually involves directly smoothing either d_L , or some other quantity with some characteristic smoothing scale. Currently there are many different models of implementing this approach [14, 15, 16]

Recently, based on smoothing the noise of supernova data over redshift, the authors in Refs. [15, 16] suggested a no-parametric method in a model independent manner to reconstruct the expansion history of our universe and the evolving properties of dark energy. In Ref. [16] two kinds of supernova data: 182 Gold dataset and 115 SNLS dataset are used firstly to reconstruct the Hubble parameter $h(z)$ ($h(z) = H(z)/H_0$) and the deceleration parameter $q(z)$. It was found that both data sets give $q(0) < 0$, which means the universe is undergoing an accelerating expansion, while the Gold set seems to favor a later entering of this accelerating era than the SNLS one. However Gold and SNLS give a good consistent constraint on the present matter density parameter Ω_{m0} ($\Omega_{m0} \approx 0.276 \pm 0.023$) when combined with the baryonic acoustic oscillation peak obtained from the large scale correlation function of luminous red galaxy in the Sloan Digital Sky Survey (SDSS) [17]. The $w(z)$ was also discussed with both kinds of SNe Ia datasets, and it was found, in agreement with that obtained in Refs. [18, 19, 20] using some parameterized models, the Gold slightly favors an dynamically evolving dark energy with a crossing of phantom divide line while the SNLS does not. However, in this method, the present value of Hubble parameter, H_0 , is needed prior or should be marginalized over. Since the value of H_0 from different observation data

seems to be inconsistent and doing the marginalization wastes the compute resources, in this paper, we firstly generalize this model independent approach to eliminate the impact of H_0 and then reconstruct the cosmic expansion history, $H(z)$, the deceleration parameter, $q(z)$, and the equation of state for dark energy $w(z)$ from the new ESSENCE Sne Ia data. Beside the 162 data points given in table 9 in Ref. [6], which contains 60 ESSENCE Sne Ia, 57 SNLS Sne Ia and 45 nearby Sne Ia, we add 30 Sne Ia detected at $0.216 < z < 1.755$ by the Hubble Space Telescope [4].

II. THE METHOD

Following a well known procedure in the analysis of large scale structure, Shafieloo et al. [15, 16] use a Gaussian smoothing function rather than the top hat smoothing function to smooth the noise of the Sne Ia data directly. In order to obtain the important information of interested cosmological parameters expediently, $\ln d_L(z)$ rather than the luminosity distance $d_L(z)$ or distance module $\mu(z)$ is studied by the following iterative method

$$\ln d_L(z)_n^s = \ln d_L(z)_{n-1}^s + N(z) \sum_i (\ln d_L^{obs}(z_i) - \ln d_L(z_i)_{n-1}^s) \exp \left[-\frac{\ln^2 \left(\frac{1+z}{1+z_i} \right)}{2\Delta^2} \right], \quad (1)$$

with a normalization parameter

$$N(z)^{-1} = \sum_i \exp \left[-\frac{\ln^2 \left(\frac{1+z}{1+z_i} \right)}{2\Delta^2} \right]. \quad (2)$$

In Eqs.(1,2) Δ is a quantity needed to be given prior. Since a large value of Δ leads to a smooth result but depresses the accuracy of reconstruction, and inversely for a small value of Δ . So it is important to choose a reasonable value of Δ . Here, as in Ref. [16], we choose $\Delta = 0.6$. In Eq.(1), $d_L(z)_n^s$ represents the smoothed luminosity distance at any redshift z after n iteration. When $n = 1$ $d_L(z)_0^s$ denotes a guess background model and it has been shown that the results are not sensitive to the chosen value of Δ and the assumed initial guess model [16]. In this paper we use a w CDM model with $w = -0.9$ and $\Omega_{m0} = 0.28$ as this guess background model. $\ln d_L^{obs}(z_i)$ is the observed one from the Sne Ia and can be expressed as:

$$\ln d_L^{obs}(z_i) = \frac{\ln 10}{5} [\mu^{obs}(z_i) - 42.38] + \ln h \equiv \ln f^{obs}(z_i) + \ln h. \quad (3)$$

Here $h = H_0/100$ and μ^{obs} is the observed distance module of Sne Ia. Apparently using the above method the nuisance parameter h needs to be given prior or marginalized over. Now we generalize this method to eliminate the impact of h . Substituting Eq. (3) into Eq. (1), we obtain that

$$\ln d_L(z)_n^s = \ln d_L(z)_{n-1}^s + N(z) \sum_i (\ln f^{obs}(z_i) - \ln d_L(z_i)_{n-1}^s) \exp \left[-\frac{\ln^2 \left(\frac{1+z}{1+z_i} \right)}{2\Delta^2} \right] + \ln h. \quad (4)$$

If defining $\ln d_L(z)_n^s = \ln f(z)_n^s + \ln h$, it is easy to see

$$\ln f(z)_n^s = \ln f(z)_{n-1}^s + N(z) \sum_i (\ln f^{obs}(z_i) - \ln f(z)_{n-1}^s) \exp \left[-\frac{\ln^2 \left(\frac{1+z}{1+z_i} \right)}{2\Delta^2} \right]. \quad (5)$$

When $n = 1$

$$\begin{aligned} \ln f(z)_1^s &= \ln f(z)_0^s + N(z) \sum_i (\ln f^{obs}(z_i) - \ln f(z)_0^s) \exp \left[-\frac{\ln^2 \left(\frac{1+z}{1+z_i} \right)}{2\Delta^2} \right] \\ &= \ln d_L(z)_0^s + N(z) \sum_i (\ln f^{obs}(z_i) - \ln d_L(z)_0^s) \exp \left[-\frac{\ln^2 \left(\frac{1+z}{1+z_i} \right)}{2\Delta^2} \right]. \end{aligned} \quad (6)$$

Here $d_L(z)_0^s$ is the luminosity distance of the suggested background model. Different from Ref.[16] to iterate through Eq.(1), we use Eq. (5) to obtain the smoothed results. The advantage of doing so is that result is independent of h (or H_0). In order to determine whether we obtain a best fit model after some iteration, we calculate, after each iteration, χ^2 :

$$\chi_n^2 = \sum_i \frac{(\mu(z_i)_n - \mu^{obs}(z_i))^2}{\sigma_{\mu_{obs},i}^2}. \quad (7)$$

Once this χ_n^2 reaches its minimum value we stop the iterative process and get the best fit result.

By differentiating the smoothed luminosity distance we can find the Hubble parameter, $H(z)$, (not $h(z)$)

$$H(z) = \left[\frac{d}{dz} \left(\frac{100f(z)}{1+z} \right) \right]^{-1}, \quad (8)$$

which contains the information of H_0 . Then the deceleration parameter $q(z)$ of the universe and the equation of state $w(z)$ of dark energy can be obtained:

$$q(z) = (1+z) \frac{H'(z)}{H(z)} - 1, \quad (9)$$

$$w(z) = \frac{[2(1+z)/3]H'/H - 1}{1 - (H_0/H)^2 \Omega_{m0}(1+z)^2}. \quad (10)$$

III. THE RESULTS

The ESSENCE program (Equation of State: Supernovae trace Cosmic Expansionan NOAO Survey Program) is designed to measure the history of cosmic expansion over the past 5 billion years. The four year data was released in Ref. [6], which contains 60 Sne Ia points. Here we use the 162 data points given in table 9 in Ref. [6], which contains 60 ESSENCE Sne Ia, 57 SNLS Sne Ia and 45 nearby Sne Ia. In addition, as in Ref. [21], we add 30 Sne Ia detected at $0.216 < z < 1.755$ by the Hubble Space Telescope [4].

Using these 192 Sne Ia data points, we find when $n = 42$ a minimum value of χ^2 is obtained which can be seen from the Fig. (1). In Fig. (2) we show the reconstructed result of the Hubble parameter $H(z)$ with the likelihood within 1σ . The red line is the best fit result and when $z = 0$ the best fit value of H_0 is $H_0 = 65.5$. Fig. (3) shows the evolving curves of reconstructed $q(z)$ with 1σ error bar. It is easy to see that the universe is undergoing an accelerating expansion since the present value of $q(z)$ is less than zero, and the phase transition from deceleration to acceleration occurs at redshift $z \sim 0.55 - 0.73$ within 1σ , which is slightly later than that obtained from Gold set ($z \sim 0.38 - 0.48$) but earlier than that from SNLS set ($z > 0.7$) [16].

Fig. (4) shows the constraint on the present matter density parameter Ω_{m0} with $H_0 = 65.5$ by combining the ESSENCE Sne Ia and baryonic acoustic oscillation(BAO) peak obtained from the large scale correlation function of luminous red galaxy in the Sloan Digital Sky Survey (SDSS). For BAO data we use a model-independent dimensionless parameter A defined as

$$A = \frac{\sqrt{\Omega_{m0}}}{h(z_1)^{1/3}} \left[\frac{1}{z_1} \int_0^{z_1} \frac{dz}{h(z)} \right]^{2/3}, \quad (11)$$

for a flat universe, where $z_1 = 0.35$ and A is measured to be $A = 0.469(\frac{n}{0.96})^{-0.35} \pm 0.017$ [17]. Here n is the spectral index of the primordial power spectrum and the WMAP3 gives $n = 0.951$ [22]. Clearly the ESSENCE Sne Ia and BAO give a strong constraint on Ω_{m0} . At the 1σ confidence level we obtain $\Omega_{m0} = 0.278^{+0.024}_{-0.023}$, which is highly consistent with that obtained from Gold+BAO and SNLS+BAO ($\Omega_{m0} = 0.276 \pm 0.023$) [16].

In Fig. (5) we plot the evolving behavior of $w(z)$ with a marginalization of Ω_{m0} over $\Omega_{m0} = 0.278^{+0.024}_{-0.023}$. The best fit (red) line shows that the ESSENCE data slightly favors an evolving dark energy with a crossing of phantom divide line at the near past, however

this evolving property is weaker than that obtained from Gold data but stronger than that from SNSL set obtained in Ref. [16]. In addition, from Figs. (3) and (5) we find that the stringent constraint on $w(z)$ and $q(z)$ happens around redshift $z \sim 0.5$, which is consistent with that obtained in Refs. [20, 23] with some parameterized models.

IV. CONCLUSION

In this paper, with a model independent method we have reconstructed the cosmic expansion history and the properties of dark energy from recent ESSENCE Sne Ia data. We firstly obtain the evolution of $H(z)$. Then the cosmic deceleration parameter $q(z)$ and the equation of state $w(z)$ of dark energy are reconstructed. Our results show that their evolutionary property reconstructed from ESSENCE data is weaker than that from Gold set, but is stronger than that from the SNSL one. Combining the ESSENCE Sne Ia and the BAO data, a tight constraint on Ω_{m0} is obtained. At a 1σ confidence level $\Omega_{m0} = 0.278^{+0.024}_{-0.023}$, which is highly consistent with that obtained from Gold+BAO and SNLS+BAO. Remarkably, as that obtained with some parameterized model [20, 23], the tight constraints on $w(z)$ and $q(z)$ seem to happen at about $z \sim 0.5$.

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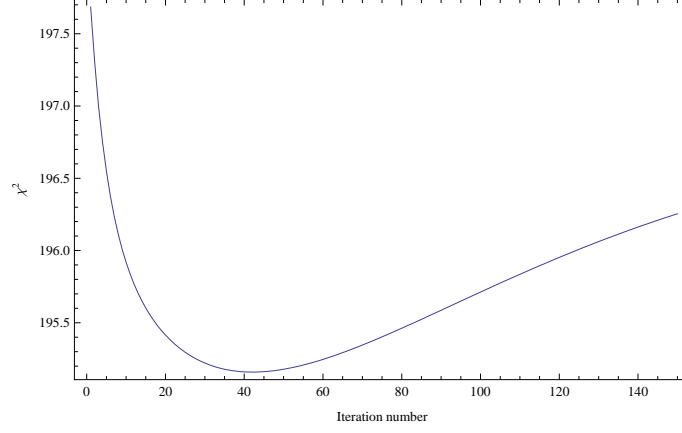


FIG. 1: Computed χ^2 for the reconstructed results at each iteration for the 192 SNe Ia data.

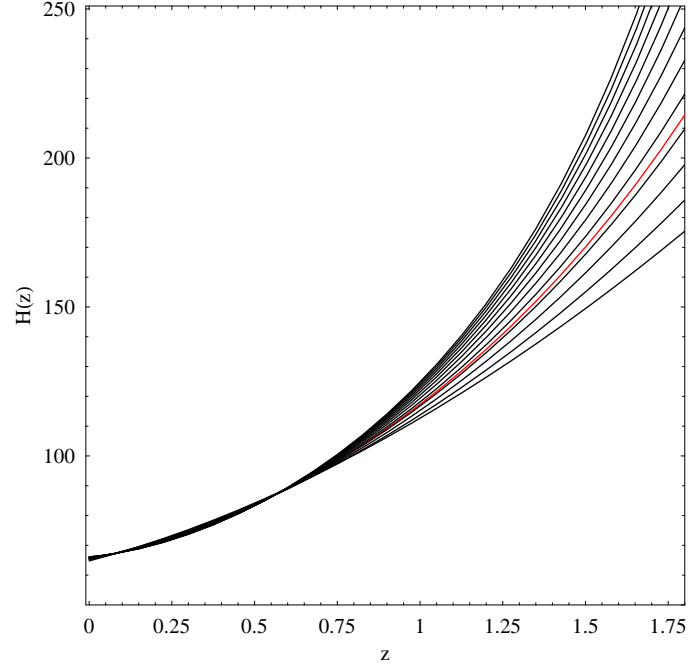


FIG. 2: The reconstructed evolutionary curves of the Hubble parameter $H(z)$ with the likelihood within 1σ . The red line is the best recovered result.

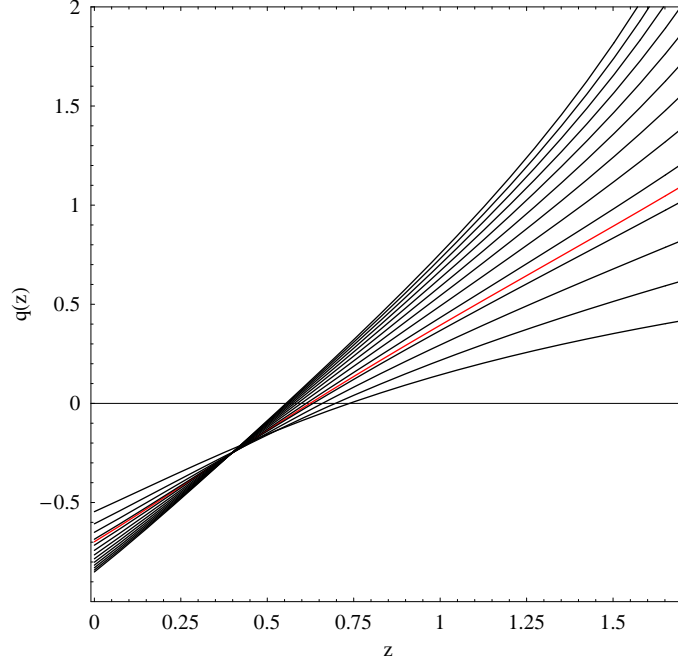


FIG. 3: The reconstructed evolutionary curves of the deceleration parameter $q(z)$ with the likelihood within 1σ . The red line is the best recovered result.

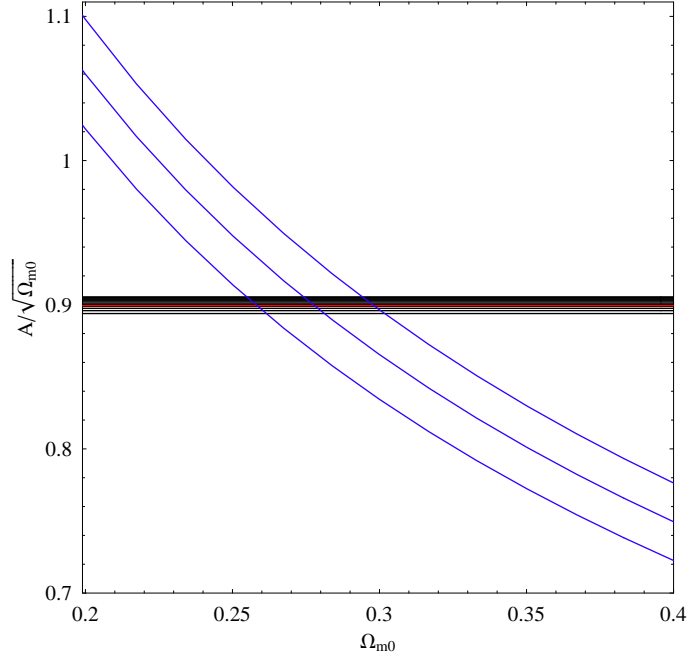


FIG. 4: The constraint on Ω_{m0} from the combination of 192 SNe Ia and BAO data. The red and black lines show the derived value of $A/\sqrt{\Omega_{m0}}$ from the 192 SNe Ia dataset within 1σ and the blue lines are the results from the BAO data.

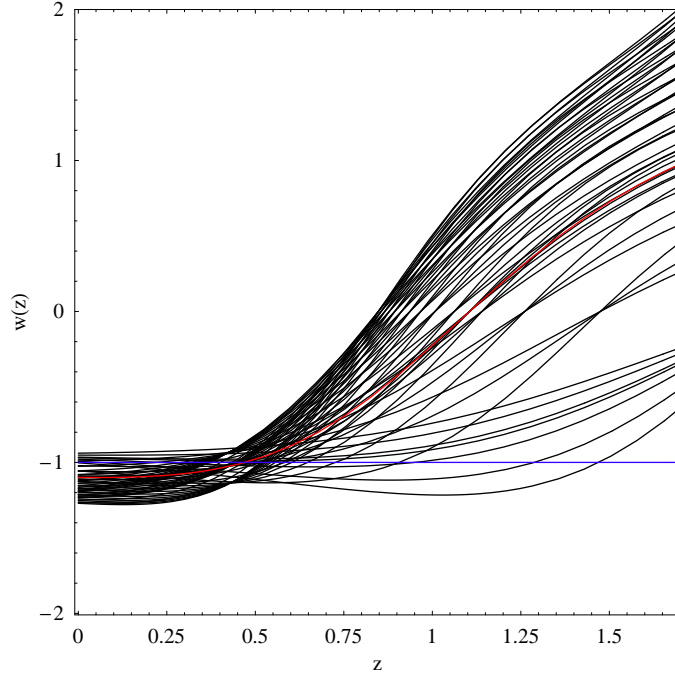


FIG. 5: The reconstructed evolutionary curves of the equation of state of dark energy, $w(z)$, within 1σ with a marginalization over $\Omega_{m0} = 0.278^{+0.024}_{-0.023}$.